

IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

Appl. No. : 10/706,192 Confirmation No. : 5984  
Applicant(s) : Frederick R. Schauer  
Filed : November 12, 2003  
TC/AU : 3748  
Examiner : Hoang Nguyen  
Docket No. : AFD 613  
Customer No. : 26902

Commissioner for Patents  
P.O. Box 1450  
Alexandria VA 22313-1450

DECLARATION PURSUANT TO 37 C.F.R. § 1.132

1. I, Scott E. Meyer, am a Senior Propulsion Engineer, employed at Purdue University, West Lafayette, IN. I am skilled in the art of pulsed detonation engines. I am also generally aware of the capabilities of others skilled in the art of pulsed detonation engines.
2. I have reviewed U.S. Patent Application Serial No. 10/706,192 (filed Nov. 12, 2003) ("the '192 Application") as well as U.S. Provisional Application Serial No. 60/426,669 (filed Nov. 12, 2002) ("the '669 Provisional Application"), the entire contents of which I understand are incorporated by reference in the '192 Application. I have also reviewed the paper entitled *Evaluation of a Hybrid Piston-Pulsed Detonation Engine*, AIAA 2002-0074, 40<sup>th</sup> Aerospace Sciences Meeting and Exhibit, Reno, Nevada (Jan. 14-17, 2002), a copy of which I understand was part of the '669 Provisional Application.

3. If I or others skilled in the art of pulsed detonation engines had access to the '192 Application and the incorporated references on or before November 12, 2002, I or they could have at that time, without undue experimentation, made and used the disclosed invention. I base this statement on my own capabilities on or before November 12, 2002, and on my understanding of the capabilities of others skilled in the art of pulsed detonation engines on or before November 12, 2002.

4. All statements in this Declaration made of Declarant's own knowledge are true and all statements made on information and belief are believed to be true. All statements are made with the knowledge that willful false statements and the like are punishable by fine or imprisonment, or both, under Section 1001 of Title 18 of the United States Code, and that such willful false statements may jeopardize the validity of this application or any patent issuing therefrom.

7/20/05  
Date

  
\_\_\_\_\_  
Scott E. Meyer



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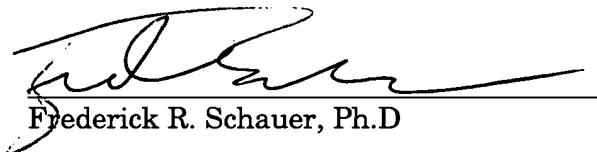
1. I, Frederick R. Schauer, Ph.D, am a Research Engineer employed at the Air Force Research Laboratory, Propulsion Directorate, Wright-Patterson Air Force Base, Ohio. I am skilled in the art of pulsed detonation engines. I am also generally aware of the capabilities of others skilled in the art of pulsed detonation engines.

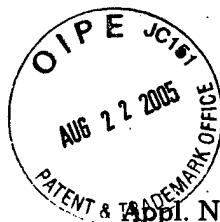
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3. If I or others skilled in the art of pulsed detonation engines had access to the '192 Application and the incorporated references on or before November 12, 2002, I or they could have at that time, without undue experimentation, made and used the disclosed invention. I base this statement on my own capabilities on or before November 12, 2002, which were demonstrated by actually making and using my invention on or before November 12, 2002, and on my understanding of the capabilities of others skilled in the art of pulsed detonation engines on or before November 12, 2002.

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18 Aug 05  
Date

  
Frederick R. Schauer, Ph.D.



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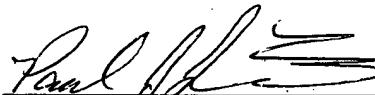
**DECLARATION PURSUANT TO 37 C.F.R. § 1.132**

1. I, Paul J. Litke, am a Research Engineer employed at Air Force Research Laboratory, Propulsion Directorate, Wright-Patterson Air Force Base, Ohio. I am skilled in the art of pulsed detonation engines. I am also generally aware of the capabilities of others skilled in the art of pulsed detonation engines.
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28 July 2005  
Date

  
PAUL J LITKE, 1LT, USAF



AIAA 2002-0474

## Evaluation of a Hybrid Piston-Pulsed Detonation Engine

Brian Frankey and Frederick R. Schauer

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Royce Bradley and John Hoke

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**40<sup>th</sup> Aerospace Sciences Meeting & Exhibit**  
**14-17 January 2002**  
**Reno, Nevada**

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AIAA 2002-0474

## EVALUATION OF A HYBRID PISTON-PULSED DETONATION ENGINE

Brian Frankey and Fred Schauer\*  
Air Force Research Laboratory, Propulsion Directorate  
Wright-Patterson AFB, OH 45433

Royce Bradley and John Hoke  
Innovative Scientific Solutions, Inc.  
Dayton, OH 45440

### Abstract

Experiments are conducted on a hybrid piston-pulsed detonation engine to evaluate the power extraction and system interaction issues. The hybrid engine is constructed using a four-cylinder motorcycle engine with a spacer block between the valves and pistons. Four detonation tubes, one for each cylinder, are placed perpendicular to the direction of the piston travel. A deflagration to detonation transition (DDT) is used to achieve detonations. The piston is in the deflagration region of the DDT. This hybrid engine has a critical starting frequency. Above this frequency the engine will self-actuate and produce excess power. Below this frequency, the power produced is less than that required to self-actuate and the engine stops rotating after the starter motor is disengaged. This hybrid piston-pulsed-detonation-engine constructed for these experiments is capable of producing 20 hp and 50 lbf of thrust simultaneously.

### Introduction

Over the past ten years, a resurgence of interest and research directed toward pulsed detonation engines (PDE) has occurred [Santoro, 2001 #106]. Recent advances in computers and diagnostic tools are allowing researchers to overcome many of the obstacles preventing the construction of a practical PDE. Depending on the application of the PDE, these obstacles include detonation initiation, valving, or designing a valveless inlet, aspiration, power extraction and others. Traditionally, the PDE has been viewed as a thrust-producing engine; however, for the PDE to work in an application like a commercial passenger jet, a second engine or power extraction from the PDE would be required to run sub-systems such as lights and air conditioning.

In this paper, a concept for extracting shaft-power from a pulsed detonation engine is described and the results of experiments conducted on the device are presented and analyzed.

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†This paper is declared a work of the U.S. Government and is not subject to copyright protection in the United States

### Experimental Apparatus and Procedure

A hybrid piston-pulsed-detonation-engine (hybrid piston-PDE) was constructed by modifying a four-cylinder four-stroke motorcycle engine. A spacer block was placed between the "head" and "block" of the motorcycle to allow for the creation of four airflow passages for the four detonation tubes. The spacer block allowed one detonation tube for each cylinder to be placed perpendicular to the travel of the piston. The 3-D cad drawing of the spacer block is shown in Fig. 1a, and a drawing of a cross section of the engine with the spacer block and detonation tube is given in Fig. 1b.

With the spacer block installed, the cam-chain and the oil supply and return lines to the "head" had to be lengthened. A picture of the assembled hybrid piston-PDE is shown in Fig 2. The spark and valve timing were altered from that of the stock engine to maximize the work output of the hybrid engine. The valve and spark timing relative to the piston position is depicted in Fig. 3.

Starting at the top of the diagram in Fig. 3 and moving clockwise, the intake valve closed approximately 15 cam-degrees after the piston had reached top dead center (TDC). A stoichiometric mixture of hydrogen and air flowed through the intake valve when it was open. At approximately 30 cam-degrees, the spark plug was fired. The stock ignition system was used to initiate deflagration of the fuel air mixture. A Shelkin shocking spiral was used to transition the deflagration to a detonation. For several milliseconds after the detonation wave exited the detonation tube, the pressure on the piston of the motorcycle was above atmospheric pressure. The spark timing was chosen to maximize the PdV work extracted by the piston. By the time the piston reached bottom dead center (BDC) the pressure on the piston had reached atmospheric pressure and the remainder of the possible "fire window" was not used. At approximately 135 cam degrees, the exhaust valve opened and purge air flowed into the cylinder and down the detonation tube to separate the hot exhaust products from the next air-fuel charge. Note that the motorcycle engine was a four-stroke, so the piston traveled up and down twice for each cycle of the camshaft. Since the exhaust products were not pushed out of the cylinder by the piston, a two-stroke engine may have been better suited for this experiment. The intake valve opened at approximately 255 cam degrees after TDC and a pre-mixed charge of air and fuel filled the combustion chamber of the motorcycle and the detonation tube, repeating the cycle. The facility air compressors were used to supply air to the hybrid piston-PDE. A piston engine is often referred to as an air pump since the motion of the piston in concert with the valve train can be used to draw in fresh air and expel exhaust products; however in the hybrid piston-PDE, the piston cannot be used to pump air since the detonation tube and hence the cylinder was always open to the atmosphere, refer to Fig 1b.

As with almost any internal combustion engine, external power is supplied to "start" the engine. In this experiment, power to start the engine was supplied by a 20 hp variable speed electric motor. A chain was used to connect the electric motor to the output sprocket of the transmission. With the transmission in gear and the clutch engaged, power from the electric motor was transmitted to the crankshaft and from the crankshaft to the camshaft via the timing chain.

With the engine rotating, the air and fuel flows were adjusted to match the detonation tube volume and engine frequency. A spark from the stock ignition system was used to ignite the fuel air mixture. Once the engine completed several cycles, the

clutch was remotely disengaged separating the “starting” electric motor from the hybrid piston-PDE. If the power extracted by the pistons was equal to the power required to rotate the crankshaft, camshaft and overcome the system friction, the rotational frequency of the hybrid piston-PDE would remain constant after the electric “starter” motor was disengaged. If excess power were produced, the rotational speed of the hybrid piston-PDE would increase. Conversely, the rotational speed of the hybrid piston-PDE would decelerate and quickly stop if the power produced was lower than the required power. As will be discussed in the “Analysis” section, a critical-starting-rotational speed must be obtained for this engine to produce enough power to self-actuate and continue to operate after the starter motor is disengaged.

### Experimental Results

Experiments were conducted to determine if the hybrid piston-PDE would operate as anticipated and to determine the power and thrust produced by the engine. In Fig 4, the detonation frequency of a single tube is plotted versus time. In this experiment, the starting frequency was above the critical starting frequency. At approximately 3.5 seconds, the clutch was disengaged and the hybrid piston-PDE accelerated from a single tube detonation frequency of approximately 11 Hz to 21 Hz. At 11 Hz, excess power was being produced which caused the rotational speed of the engine to accelerate. At 21 Hz, the hybrid engine reached a new equilibrium where the power required to actuate the engine was equal to the power produced by the engine. The air and fuel flow were set for operation at 11 Hz and at 21 Hz, the air and fuel flow would be approximately  $\frac{1}{2}$  that required to completely fill the detonation tube prior to detonating. The control system for the air and fuel could not keep up with the rapid change in operating frequency of the hybrid engine. The experiment was automatically terminated at 9 seconds because the temperature of the detonation tubes exceeded a preset limit. In this experiment, a 72" detonation tube with a 1.84 to 1 converging nozzle was used.

At a starting frequency below the critical starting frequency for a 36" detonation tube without a nozzle, the engine did not self-actuate. In Fig. 5a, the frequency of the engine, normalized by the critical frequency determined experimentally, is plotted versus time. At approximately 1.7 seconds, the clutch was disengaged and the engine quickly decelerated. The power produced by this configuration is plotted in Fig. 5b. While the hybrid engine was being driven by the electric starter motor, the hybrid engine was producing approximately 8 hp—not enough to self-actuate. The power produced was calculated by integrating the pressure in the cylinder head along with the piston movement.

The maximum power produced by this hybrid engine was approximately 20 hp while still producing 50 lbf of thrust. In Fig. 6a, the frequency of this run normalized by the critical frequency is plotted verses time. Notice that the engine was operating well above the critical frequency. The power and thrust produced by this engine are plotted in Fig 6b and c respectively.

### Analysis

As evident in the experimental results, there was a starting frequency above which the hybrid piston-PDE would self-actuate and continue to operate after the electric “starter” motor was disengaged. Below this critical frequency the hybrid engine would

quickly stop. The critical frequency for this hybrid engine was a result of the different time constants for the piston movement and the detonation tube "blow down" event. The time constant for the piston engine is defined as

$$t_p = \frac{2}{f_{crank}} \quad (1)$$

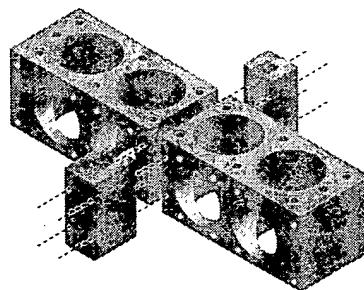
where  $f_{crank}$  is the frequency of the crankshaft, and the time constant for the "blow down" event is the time required for the pressure in the detonation tube to decrease to 1/3 of the gage pressure behind the detonation wave.

The time constant of the blow-down event can be altered by changing the length of the detonation tube or installation of a nozzle at the end of the detonation tube, while the time constant of the piston movement can be altered by changing the operating frequency of the engine. For most of the conditions tested the time constant of the detonation-tube-blow-down was smaller than that of the piston movement. If the time constants were too different the blow down process would occur while the piston would effectively be stationary; therefore little or no PdV work would be extracted from the detonation pressure. By increasing the starting frequency, and lengthening the detonation tube, the time constants of the piston movement and blow down process were similar enough that the work extracted by the piston exceeded the requirement to self-actuate. In Fig. 7, a diagram of the hybrid-engine-timing is given for two different operating frequencies. From these diagrams, it can be seen that at the higher frequencies, the blow down process occurs over a larger portion of the piston movement.

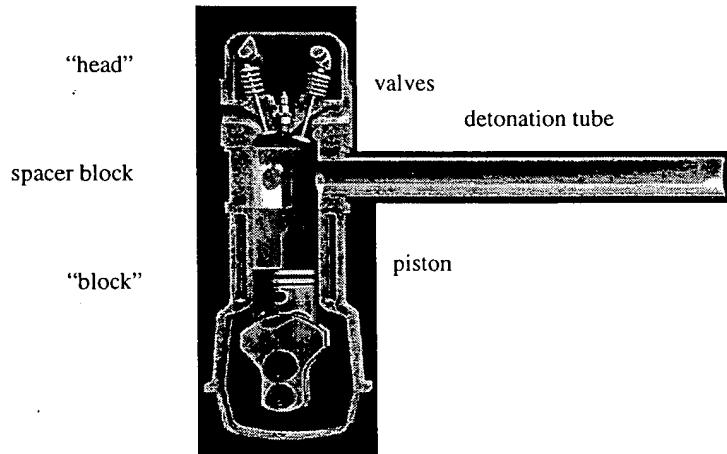
The critical frequency of the hybrid piston-PDE was calculated by estimating the power required for self-actuation and equating that with the PdV work extracted as a function of frequency. The power required for self-actuation included the power required for the system friction and the power required to open and close the valves. Estimates for the power required were taken from Heywood [1988 #111]. Figure 8, shows the power required plotted and the power produced as a function of the normalized frequency. The critical frequency for this particular experiment was calculated to be a detonation frequency of 5 Hz which was within a hertz of the experimentally determined value. A better method for determining the system requirements would be to test the required power on a dynamometer.

The ideal thermodynamic piston-PDE cycle consists of a constant volume heat addition process (0-1) followed by an isentropic expansion process (1-2). In Fig. 9a the ideal T-s diagram for the hybrid piston-PDE is given and in Fig. 9b the ideal P-v diagram is given. This cycle is very similar to the Air-Standard Otto cycle except there is no isentropic compression of the working fluid before the constant volume heat addition. Of course the method for achieving constant volume combustion is significantly different. This cycle would be impractical for constant pressure combustion. A good discussion of PDE cycle efficiency and the advantage of constant volume versus constant pressure combustion are given by Bussing and Pappas [1994 #40]. The thermal efficiency of the hybrid piston-PDE is given by Eq. (1).

Thanks to Charley Smith for his consultations. The authors would also like to thank Jeff Stutrud and Jason Parker for their computer programs used to collect and analyze the data, and Mike Bruggeman for his artistic drawing of the hybrid piston-PDE shown in Fig. 1b. The authors would also like to acknowledge the technical leadership of Dr. Mel Roquemore and Dr. Robert Hancock (AFRL/PRTS).



(a)



(b)

Figure 1      Spacer bock: a) 3D cad drawing and b) Drawing of a cross section of the assembled hybrid piston-PDE

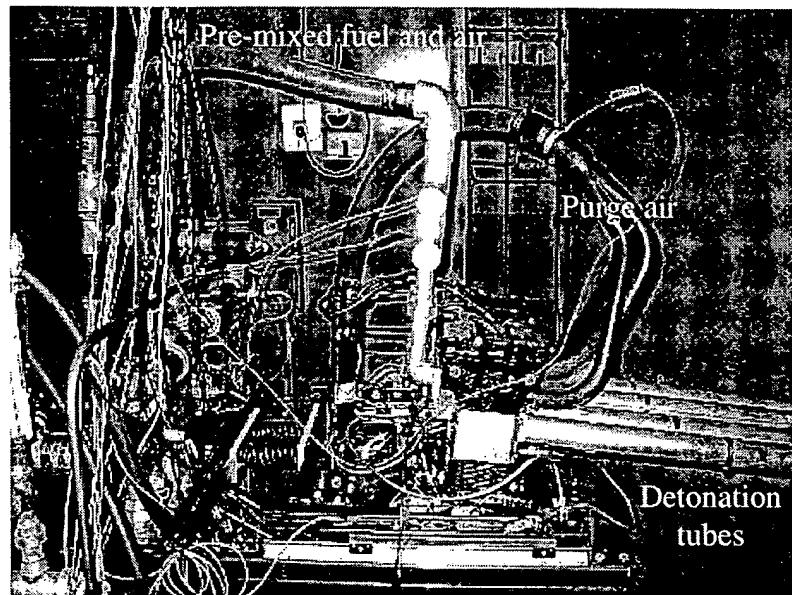


Figure 2 Picture of the hybrid piston PDE

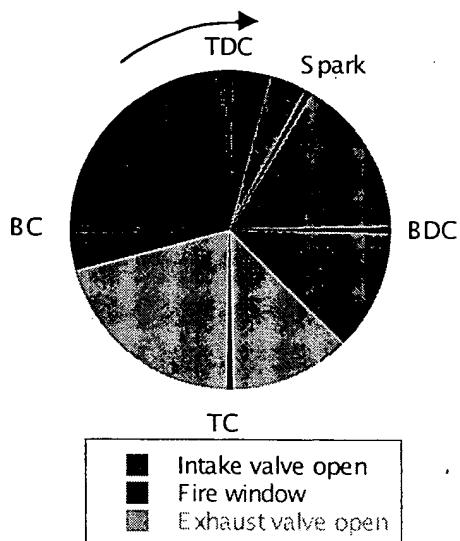
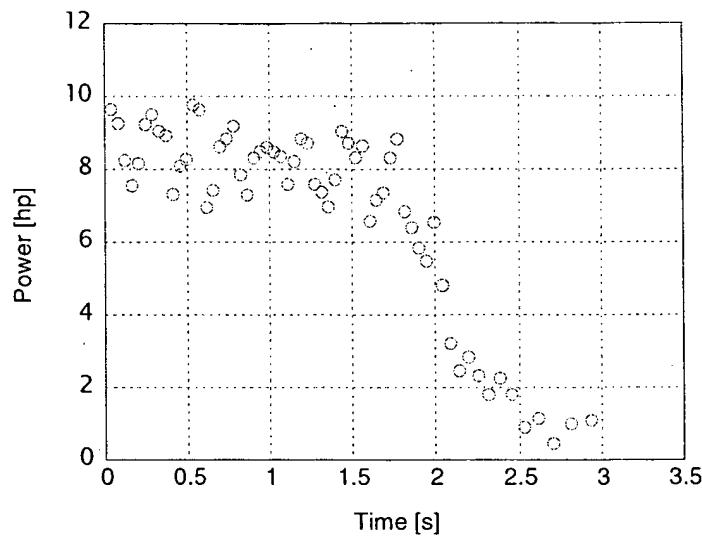
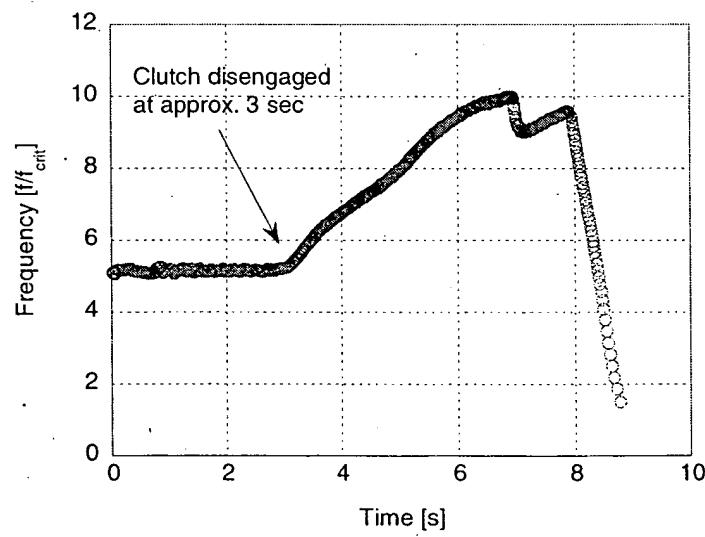


Figure 3 Valve and spark timing relative to piston position, note that the crankshaft makes two revolutions for every one that the camshaft makes. (TDC is top dead center, BDC is bottom dead center, TC is top center and BC is bottom center)



(b)

Figure 5 Below the critical starting frequency the hybrid piston-PDE failed to self-actuate, (a) normalized frequency verses time and (b) calculated power output during this experiment



(a)

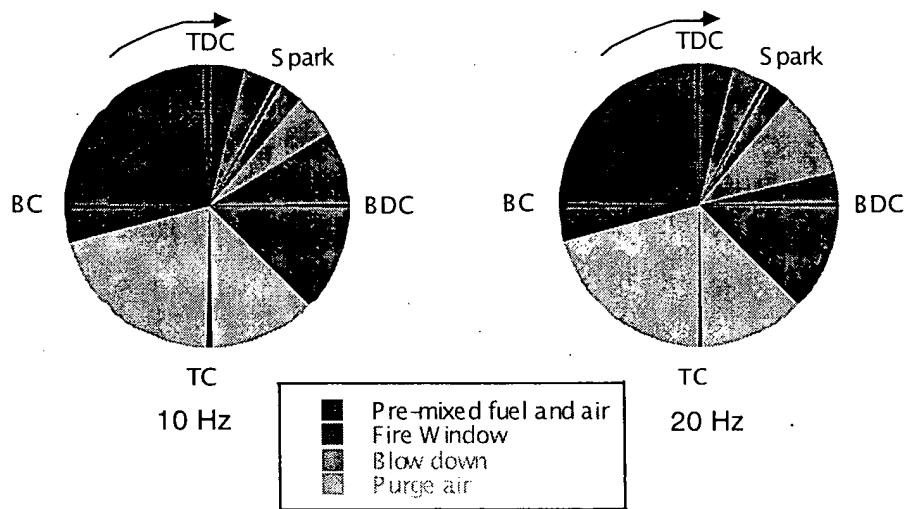


Figure 7 Engine timing and pressure during a cycle at two different frequencies

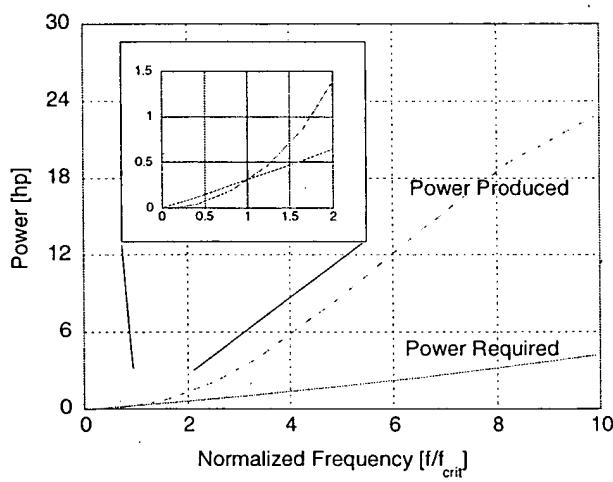


Figure 8 Hybrid piston-PDE critical frequency

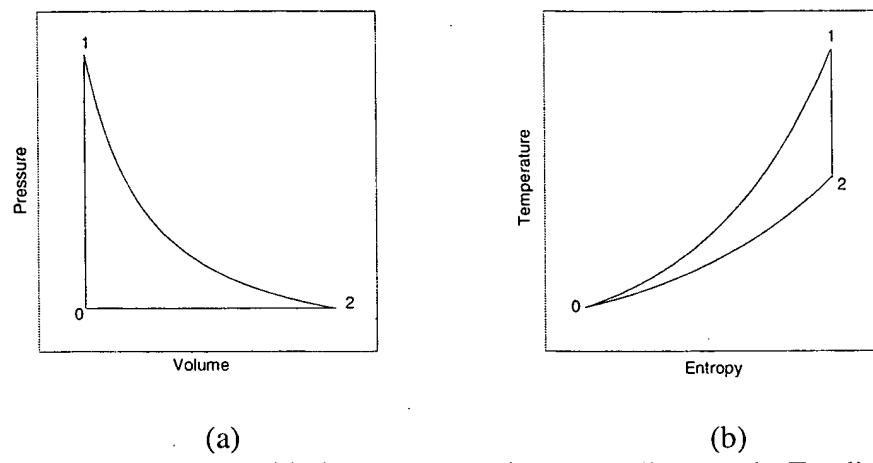


Figure 9 Ideal hybrid piston-PDE cycle: a) P-v diagram, b) T-s diagram

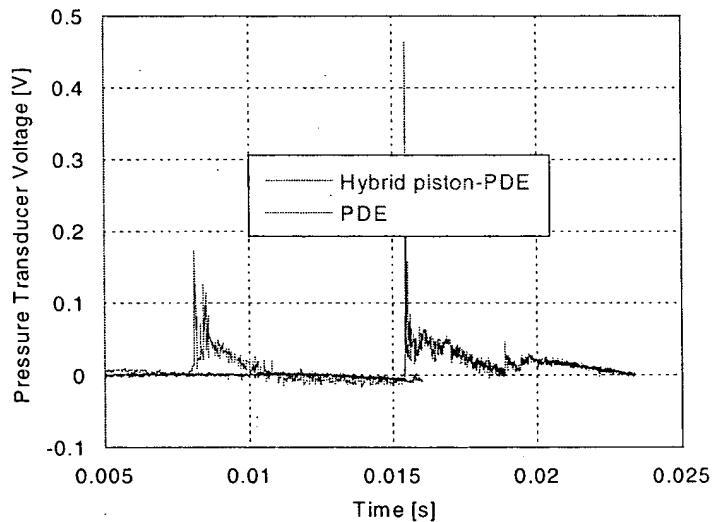


Figure 10 Pressure transducer voltage near the closed end of the detonation tube